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Optimization of the operating cost of sewage conveyance

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Abstract

Accelerated urbanization places extraordinary demands on sewer networks; thus optimization research to improve the design of these systems has practical significance. In this paper, a subsystem nonlinear programming model is developed to optimize the operating cost of sewage conveyance. The subsystem model is expanded into a large-scale complex nonlinear programming system model to find the minimum total annual cost of the pumping station and network of all pipe segments. Large system test selection and subsystem dynamic programming methods are described in this paper. As an example, a comparative analysis is conducted using the sewage network in Taizhou city, China. The proposed method demonstrated that significant cost savings could have been realized, if the studied system had been optimized using the techniques described in this paper, and the annual cost of sewage conveyance engineering in the case could have been reduced by 10.2%. Thus, the method has practical value for optimizing urban sewage projects and provides a reference for theoretical research about optimization of urban drainage pumping station layouts.

Keywords: Dynamic programming; nonlinear optimization; orthogonal test; pressurized pumping station; sewage pipe network.

1. Introduction

In recent years, rapid economic development has placed additional demands on China's wastewater infrastructure. In many cities, the high operational cost of sewage conveyance has seriously affected the improvement of the environment of the city, which is closely related with the city›s economic prosperity. Thus, optimization of the operation cost of sewage conveyance engineering has very considerable practical significance and economic value.

Currently, few studies on the optimization of municipal sewage pumping station layout and sewage pipe network design have been conducted, either in China or internationally. Marchionni et al. (2014) proposed a mathematical model to optimize and design the sewage pipe system based on the multiple linear regression analysis method, with the pipe diameter and buried depth taken as the decision variables, and the construction cost of the sewage pipeline project as the objective function. Afshar & Rohani (2012) designed a nonlinear programming mathematical model based on a cellular automata simulation algorithm to optimize a sewage pipe network, with the diameter and buried depth of sewage pipe employed as the decision variable, and the cost of the construction as the objective function. Joseph-Duran et al. (2014) built a mathematical model using mixed integer linear programming based on the simulation of the rolling horizon optimal control of a sewage pipe network. Yeh et al. (2011) proposed a mathematical model for the optimal design of a sewage pipe network using Tabu Search and Simulated Annealing; the network was designed to minimize the cost of a sewage pipe network by meeting the requirements of the maximum and minimum flow rate of sewage. Chaball & Stanko (2014) proposed a mathematical model to optimize the running cost of a sewage pumping station; the model included simulation of variable-frequency speed change of a sewage pump to target the high running cost of some sewage pumping stations. Haghighi & Bakhshipour (2014) developed an integrated optimization model for the optimal design of a sewage collection pipe network based on Tabu Search, with the layout of the pipe network and pipe diameter employed as the decision variables and the construction cost of the pipe network as the objective function. Erkan et al. (2008) proposed an irrigation system planning model for use in arid and semi-arid areas with the land consolidation, through the use of Logit regression analysis, to reduce the running cost of an irrigation system and improve the irrigation system water use efficiency.

Most of the existing studies have been concerned with reducing the construction cost of a sewage pipe network, and few have given equal attention to the operating cost of sewage conveyance and the design of sewage pumping stations layout. In contrast, this paper is primarily concerned with the operating cost of sewage conveyance and the layout of a sewage pumping station. A dynamic programming method is proposed for the specification of a subsystem sewage pipe network and an optimization experiment is conducted on the design of the sewage pumping station. This technique represents a new method for the optimization of a sewage pipe network and sewage pumping station layout.

2. The optimization model and solution method

Urban sewage is collected and transported to the main pipe via branch pipes, and then transported to one or more wastewater treatment plants through the main pipe network. Pumping stations are typically required on main lines (and sometimes on branch lines) and together with the pipe network, form the urban sewage collection and delivery system. Sewage from the dry pipe into the main pressure pipeline should be compressed by a small lifting pump station. This paper is aimed at optimizing the layout of the sewage pumping stations and sewage pipe network as suggested in the study by Haghighi & Bakhshipour (2012).

Compared with the annual cost of a branch pipe network without pumping stations, the cost of the main pipe network includes those costs related to pumping stations (construction investment, energy, maintenance, management and residual value) as well as those for the pipe network (construction investment, maintenance and management). In pressurized-flow networks that include pumping stations, the buried pipe depth is relatively unaffected by slope and therefore change of the buried depth is not considered in design calculations. However, in branch pipe networks without pumping stations (i.e., gravity-flow networks) the buried pipe depth is greatly influenced by slope, and the slope and buried depth must be taken into consideration in design calculations. The flow of sewage in a pressurized-flow network completely fills the pipe, while that in a gravity-flow network typically only partially fills the pipe and the full scale of the network should be taken into account (Karovic & Mays, 2014; Sebti & Bennis, 2012). A schematic map of a hypothetical sewage pipe network system with pumping stations is shown in Figure 1, and the relationship between working lift and head loss is illustrated in Figure 2.

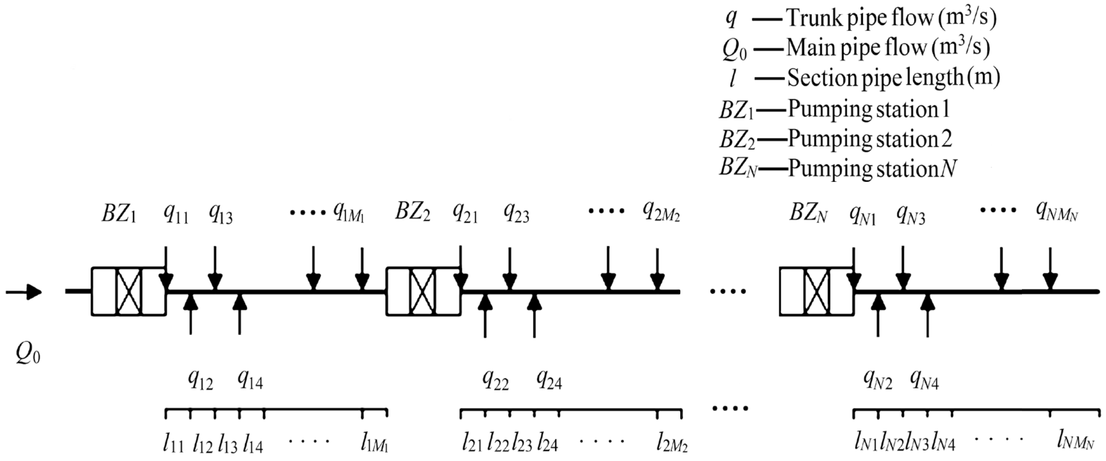

Fig. 1. Hypothetical sewage pipe network system with pumping stations.

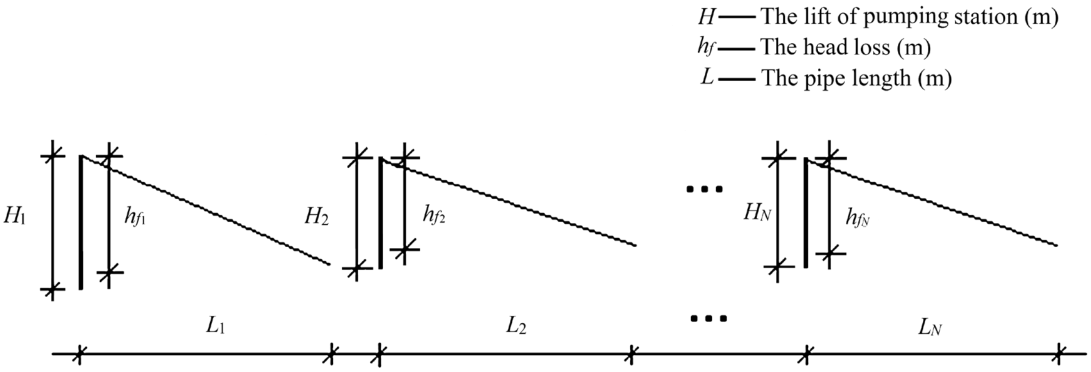

Fig. 2. The relationship between working lift and head loss.

2.1 Mathematical models

Mathematical models for the optimal design of a sewage pipe network are established for both a single pipe segment (the subsystem model) and for all pipes and sewage pumping stations (the large-scale system model). In the models the minimum annual costs of the pipe network and pumping stations are the objective functions, the pumping station and the corresponding main pipe section are the stage variables, the diameter of the branch pipe and the head of the pumping station are the decision variables, and the head loss of the all pipes, the flow velocity and the diameter of branch pipes of the sewage pipe network are the constraints.

2.1.1 Subsystem model

The subsystem model addresses the optimization problem of each pipe section of the sewage pipe network and pumping stations. The objective function F_i of the annual cost of the sewage pipe network and pumping stations for pipe section i is described by Equation (1):

$$F_i = \min[(\alpha+\beta+\theta)(C_i+P_i)+\frac{ET\rho gQ_iH_i}{\eta}-\frac{\alpha\gamma P_i}{(1+r_0)^t}] \qquad (1)$$

Likewise, the construction cost C_i of the main pipes of the sewage pipe network in pipe section *i* is defined by Equation (2):

$$C_i = \sum_{j=1}^{M_i}(a_1+a_2D_{ij}^{\ 2}+a_3h_{ij}^{\ 2})l_{ij} \qquad (2)$$

The construction investment P_i for sewage pumping station *i* is defined by Equation (3):

$$P_i = \begin{cases} 0 & H_i = 0 \\ b_1+b_2Q_i+b_3Q_i^2+b_4H_i^{\ 2} & H_i \neq 0 \end{cases} \qquad (3)$$

In Equations (1) – (3), F_i is the minimum annual cost of the sewage pipe network and pumping stations of pipe section i (yuan); Dij is the diameter of branch pipe section j of pipe section i (m); hij is the buried depth of branch pipe section j of pipe section i (m); lij is the pipe length of branch pipe section j of pipe section i (m); Qi is the daily maximum flow of sewage pumping station i (m3 s-1); Hi is the head of sewage pumping station i (m); Mi is the total number of branch pipe sections within pipe section i of the sewage pipe network; a_1, a_2, a_3, b_1, b_2, b_3 and b_4 are constants calculated by the least squares method of the trend surface; α is the equivalent annuity coefficient $\frac{r_0(1+r_0)^t}{(1+r_0)^t-1}$ in which r0 is the local average rate of return (%) and t is the design engineering service life; E is the energy consumption unit price (yuan kWh-1); T is the operating duration of the sewage pumping station (h); ϱ is water density (1000 kg m-3); g is acceleration of gravity (9.8 m s-2); η is the overall efficiency of the pumping station; β is the annual maintenance cost coefficient of the main pipe network and sewage pumping stations; θ is the annual management fee coefficient of the main pipe network and sewage pumping stations; and γ is the ratio of the residual value of the sewage pumping stations to the initial value.

The constraints in the subsystem model include (a) head loss at both ends of the pipe section, (b) economical flow velocity of the branch pipe section and (c) the diameter of the branch pipe section.

(a) The head loss constraint at both ends of the pipe section is defined by Equation (4):

$$h_{f_a} \le H_i - \sum_{j=1}^{M_i}\lambda k_{ij}\frac{Q_{ij}^{n_{ij}}}{D_{ij}^{m_{ij}}}l_{ij} \le h_{f_b} \qquad (4)$$

In which λ is the magnification coefficient of local head loss; kij, nij, and mij are the resistance coefficients of branch pipe section j of pipe section i, and are related to pipe characteristics; Qij is the daily maximum flow of branch pipe section j of pipe section i (m3 s-1); and hfa and hfb are, respectively, the minimum and maximum permissible deviation of the head loss in pipe section i and head of the sewage pumping station.

(b) The constraint for economical flow velocity in the branch pipe section is defined by Equation (5):

$$V_{\min} \le V_{ij} \le V_{\max} \qquad (5)$$

In which Vmin is the minimum allowable velocity of the pipe section (m s^{-1}); Vij is the flow velocity of branch pipe section j of pipe section i (m s^{-1}), namely, $V_{ij} = 4Q_{ij}/(\pi D_{ij}^2)$; and Vmax is the maximum permissible flow velocity of the pipe section (m s^{-1}). Generally, and in the model, Vmax is taken as 5 m s^{-1}, this velocity prevents water hammer; and Vmin is taken as 0.6 m s^{-1}, the velocity required to prevent deposition of suspended substances along the bottom of pipes.

(c) The constraint on the diameter of the branch pipe section is defined by Equation (6):

$$D_{\min} \le D_{ij} \le D_{\max} \qquad (6)$$

In which Dmin and Dmax are, respectively, the minimum and maximum allowable pipe diameters (m) and Dij is the diameter of branch pipe section j of pipe section i (m). The diameter of pressurized sewage pipe should meet the requirements of the corresponding optional standard diameter set.

Optimal method of solution for the subsystem model. Using Equations (1) – (6), if H (the head on pumping station i) is known, then the model is transformed into a one-dimensional dynamic programming problem with a one-dimensional coupling constraint Equation (4), which can be solved by the classical method (Cheng et al., 2010; Gong et al., 2015; Steele et al., 2016; Zhang & Cheng, 2006).

2.1.2 Large-scale system model

The large-scale system model allows optimization of the sewage pipe network and the layout of pumping stations. The objective function of the annual cost of the large-scale system model is defined by Equation (7):

$$F = \sum_{i=1}^{N} F_i \qquad (7)$$

In which F is the minimum cost of the sewage pipe network project and the sewage pumping stations; and N is the total number of the pipes in the sewage pipe network project.

The constraints in the large-scale model include (a) head loss, (b) flow velocity, and (c) the diameter of the branch pipe. As in the subsystem model, these constraints are calculated using Equations (4) – (6).

Optimal method of solution for the large-scale model. The orthogonal test is a scientific test for multi-factor experiments. It uses the normalization of the orthogonal table to arrange the test, and can be used to determine the optimal solution. The orthogonal test results can be analyzed simply (by counting) and will provide a comprehensive and systematic approach to support good judgements.

In the large-scale system model, the head H of the sewage pumping station is taken as the decision variable. If H is known, then the problem can be transformed into N subsystem optimization problems. In this paper, the orthogonal test method is adopted to optimize the head H of each sewage pumping station. If the head is equal to 0, then the optimization of the layout of the pumping stations can be achieved by finding the optimal head of the pumping stations (Abdelsalam et al., 2010; Afshar et al., 2010; Brand & Ostfeld, 2011; Liu et al., 2010; Su & Yao, 2004).

2.2 Optimal steps in using the subsystem and large-scale system models

Step 1: Confirmation of the test scheme. The number (N) of the sewage pumping stations is taken as the test factor. Alternative heads (Hi) of pumping stations are taken as the test level. Orthogonal arrays are selected to determine the combination of heads for each sewage pumping station (Cheng et al., 2004; Shi et al., 2014).

Step 2: Optimization of the subsystem. When the head is known, the one-dimensional dynamic programming method is adopted to solve Equations (1) – (6) and calculate the optimal set value of the diameter of each branch pipe section Dij(Hi) (i=1, 2, …N□j=1, 2, …Mi) and the total annual cost F(Hi).

Step 3: Orthogonal test selection. The range method is employed to address the corresponding annual cost in different test combinations of head to determine the theoretically optimal combination of heads Hi*.

Step 4: Once Hi* is known, the optimal diameter of the pipe Dij* and the minimum annual cost of pumping stations and sewage pipe network project F* can be calculated using the method described in Step 2.

The graphical representation of the above solution process is shown in Figure 3.

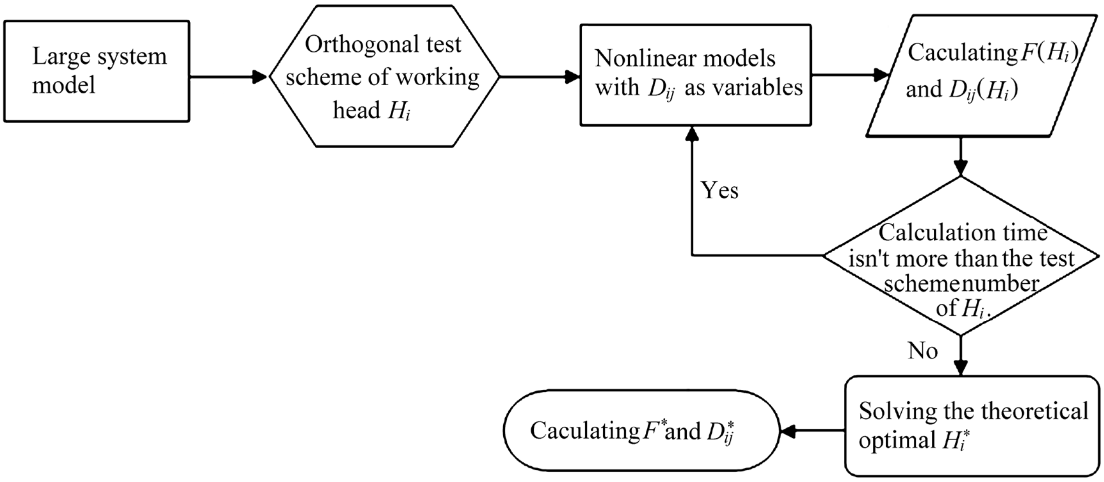

Fig. 3. The process of solving the large-scale system model.

3. Application of optimization method to a test project

3.1 Project description

The test project consists of the sewage pumping stations and sewage pipe network in a developing municipal region in Taizhou, China. Because of the systematic sewage pipe network in the old district of the city, wastewater from the new district has to bypass the old district, when being transported to treatment plants. The prerequisite is that the sewage from the dry pipe into the main pressure pipeline should be compressed by a small lifting pump station. The pipe is made of fiberglass reinforced plastic mortar. Steel pipes are used in the areas, where lines must cross a road or river. The local average rate of return on investment r0 should be 10%. The service life of the project t should be 20 years. The annual maintenance cost coefficient of the sewage pipe network and pumping stations should be 2%, and the annual management cost coefficient should be 1%. The local pressurized sewage pipe network layout is shown in Figure 4. The generalized diagram of the pressurized piping system is shown in Figure 5. The length of each pipe segment is described in Table 1.

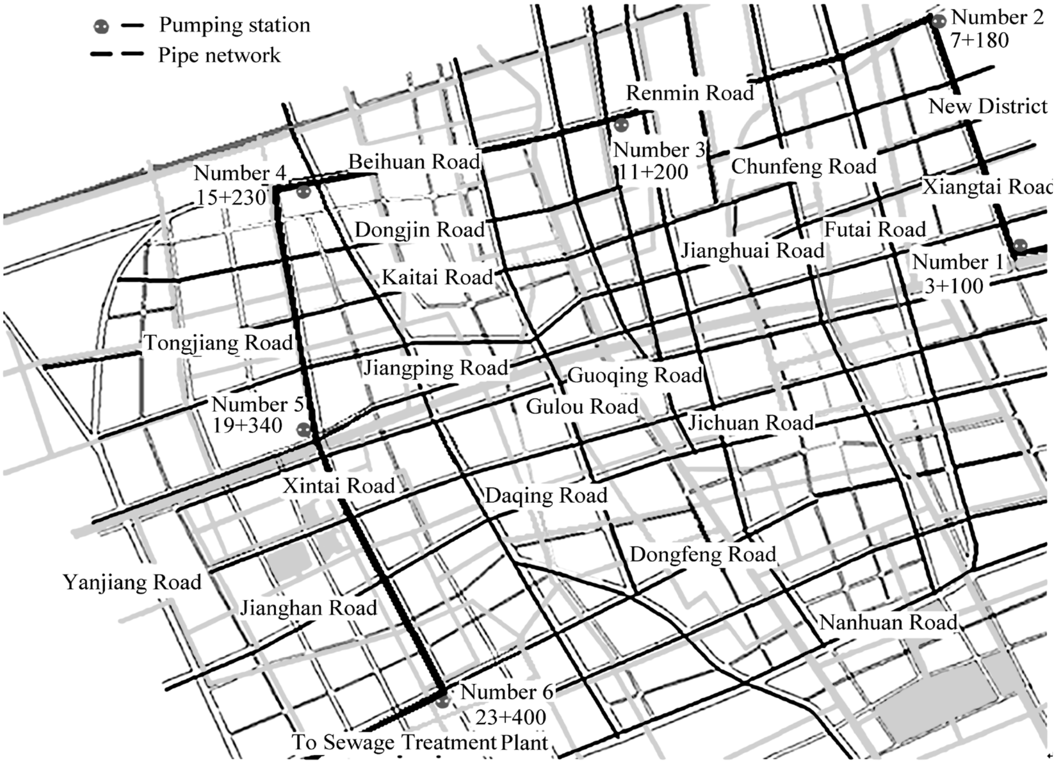

Fig. 4. Local pressurized sewage pipe network layout.

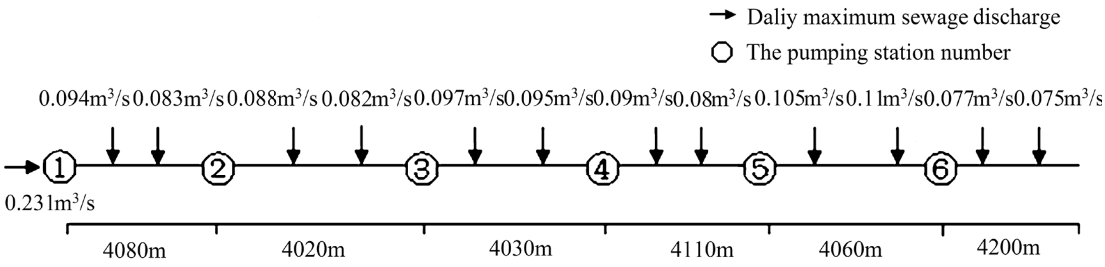

Fig. 5. Generalized diagram of the pressurized piping system.

Table 1. Pipe length of each pipe segment in the pressurized piping system.

Pipe segment number	Pipe segment name	Section pipe segment name	Length (m)
1	Node 1 – node 2	Divided pipe segment 1	1300
		Divided pipe segment 2	1400
		Divided pipe segment 3	1380
2	Node 2 – node 3	Divided pipe segment 1	1300
		Divided pipe segment 2	1380
		Divided pipe segment 3	1340
3	Node 3 – node 4	Divided pipe segment 1	1300
		Divided pipe segment 2	1370
		Divided pipe segment 3	1360
4	Node 4 – node 5	Divided pipe segment 1	1320
		Divided pipe segment 2	1400
		Divided pipe segment 3	1390
5	Node 5 – node 6	Divided pipe segment 1	1300
		Divided pipe segment 2	1400
		Divided pipe segment 3	1360
6	Node 6 – sewage plant	Divided pipe segment 1	1360
		Divided pipe segment 2	1410
		Divided pipe segment 3	1430

3.2 Solution procedures and optimization result

Step 1: Test factors, test level and orthogonal table selection

Taking pumping stations as the test factor, the project has six test factors (i.e., six pumping stations). Also, according to the actual situation, there can be five levels of head at a pumping station (0, 1, 2, 3 and 4 m). Therefore, a 6 × 5 (factors × levels) orthogonal table is selected, which is the L25 (56) type orthogonal table in which number of all possible combinations is 56. A theoretically optimal solution of the 15625 combinations can be found after implementing the 25 test schemes according to the orthogonal table. The test combinations of pumping head and the corresponding cost (target value) are illustrated in Table 2.

Table 2. Test combinations of pumping head for six pumping stations and the corresponding target value (cost).

Test scheme	The test level of the working head of six pumping stations (m)						Target value (Yuan)
	1	2	3	4	5	6	
1	0	0	0	0	0	0	8382412*
2	0	1	1	1	1	1	8338468
3	0	2	2	2	2	2	8270433
4	0	3	3	3	3	3	8177206
5	0	4	4	4	4	4	8188678
6	1	0	1	2	3	4	8277361
7	1	1	2	3	4	0	8288519
8	1	2	3	4	0	1	8438272
9	1	3	4	0	1	2	8256259
10	1	4	0	1	2	3	8284784
11	2	0	2	4	1	3	8357916
12	2	1	3	0	2	4	8368004
13	2	2	4	1	3	0	8237731
14	2	3	0	2	4	1	8308255
15	2	4	1	3	0	2	8278298
16	3	0	3	1	4	2	8318151
17	3	1	4	2	0	3	8418299
18	3	2	0	3	1	4	8278692
19	3	3	1	4	2	0	8338578
20	3	4	2	0	3	1	8264606
21	4	0	4	3	2	1	8268634
22	4	1	0	4	3	2	8359517
23	4	2	1	0	4	3	82085327
24	4	3	2	1	0	4	8329021
25	4	4	3	2	1	0	8409222

*The target value of test scheme 1 is calculated using the hydraulic formula for a non-pressurized pipe network.

Step 2: Subsystem selection

After putting 25 combinations of the working head from Table 2 into Equations (1) – (6) in turn, the optimal value of the diameter Dij(Hi), and the corresponding target value of the annual cost of sewage pipe network and pumping station F(Hi) can be obtained by using the one-dimensional dynamic programming method; these also are given in Table 2. The decision variable diameter Dij is discrete by the optional standard of economic flow rate, which is described in Table 3.

Table 3. Optional standard pipe diameters and optimized size of each pipe segment.

Pipe segment name	Section pipe segment name	Optional standard pipe diameter (m)											Optimized diameter (m)
Node 1 – node 2	Divided pipe segment 1	0.4	0.5	0.6	0.7	0.8	—	—	—	—	—	—	0.7
	Divided pipe segment 2	0.4	0.5	0.6	0.7	0.8	—	—	—	—	—	—	0.7
	Divided pipe segment 3	—	0.5	0.6	0.7	0.8	0.9	—	—	—	—	—	0.8
Node 2 – node 3	Divided pipe segment 1	—	0.5	0.6	0.7	0.8	0.9	—	—	—	—	—	0.8
	Divided pipe segment 2	—	0.5	0.6	0.7	0.8	0.9	1.0	—	—	—	—	0.9
	Divided pipe segment 3	—	—	0.6	0.7	0.8	0.9	1.0	—	—	—	—	0.9
Node 3 – node 4	Divided pipe segment 1	—	—	0.6	0.7	0.8	0.9	1.0	—	—	—	—	0.9
	Divided pipe segment 2	—	—	0.6	0.7	0.8	0.9	1.0	—	—	—	—	0.9
	Divided pipe segment 3	—	—	—	0.7	0.8	0.9	1.0	1.2	—	—	—	1.0
Node 4 – node 5	Divided pipe segment 1	—	—	—	0.7	0.8	0.9	1.0	1.2	—	—	—	1.0
	Divided pipe segment 2	—	—	—	0.7	0.8	0.9	1.0	1.2	—	—	—	1.0
	Divided pipe segment 3	—	—	—	0.7	0.8	0.9	1.0	1.2	1.4	—	—	1.2
Node 5 – node 6	Divided pipe segment 1	—	—	—	0.7	0.8	0.9	1.0	1.2	1.4	—	—	1.0
	Divided pipe segment 2	—	—	—	—	0.8	0.9	1.0	1.2	1.4	1.5	—	1.0
	Divided pipe segment 3	—	—	—	—	0.8	0.9	1.0	1.2	1.4	1.5	—	1.2
Node 6 – sewage plant	Divided pipe segment 1	—	—	—	—	0.8	0.9	1.0	1.2	1.4	1.5	—	1.0
	Divided pipe segment 2	—	—	—	—	0.8	0.9	1.0	1.2	1.4	1.5	1.6	1.2
	Divided pipe segment 3	—	—	—	—	0.8	0.9	1.0	1.2	1.4	1.5	1.6	1.2

Step 3: Theoretically optimal combination of head obtained by range analysis

An analysis of test indexes for different levels of a single factor is conducted by 25 combining test plans of the working head of the pumping stations in the L25 (56) orthogonal table. The corresponding mean values of the index values for each factor under different test levels (k1, k2, k3, k4 and k5) and the range are given in Table 4. The theoretically optimal test plan can be obtained when k is small. The theoretically optimal combination of the head for the 56 combinations Hi* can be determined using range analysis (H1* = 0 m; H2* = 3 m; H3* = 4 m; H4* = 3 m; and H5* = 4 m).

Table 4. Range analysis table.

Test scheme	The corresponding mean values of the index values for each factor under different test levels (Yuan)					
	1	2	3	4	5	6
k1[a]	8271440*	8320895	8322732	8295963	8369261	8331292
k2	8309039	8354561	8288248	8301631	8324111	8323647
k3	8310041	8286732	8302099	8336714	8306086	8296532
k4	8323665	8281864*	8342171	8258270*	8263284	8289347
k5	8314985	8285118	8273920*	8336592	8262427*	8288351*
R[b]	52225	72697	68251	78444	106834	42941

[a] k1, k2, k3, k4 and k5 are the corresponding mean values of the index values for each factor under different test levels.

[b] R is the variation range of the test index of the factor in the range of its value.

*The asterisk denotes the optimal level combination.

Step 4: Large-scale subsystem optimization

The optimal diameter of each branch pipe section Dij* can be determined by putting the theoretically optimal combination Hi* of the working head of the pumping stations into Equations (1) – (6), which is illustrated in Table 3. The corresponding minimum target value of the annual cost of the sewage pipe network and pumping stations is 7,478,949 yuan. The relationship between the head of the pumping stations and the total annual cost is presented in Figure 6.

In the original sewage network plan, the pumping station heads were set to known values (H1=3 m; H2=3 m; H3=3 m; H4=3 m; H5=3 m; and H6=3 m), which is not an optimized design of the layout of the pumping stations. According to the model represented by Equations (1) – (6), the diameter of the pipe network is optimized using the one-dimensional dynamic programming method. Rather, the use of fixed pumping station heads only optimizes the pipe diameter, and the corresponding annual cost of the sewage pipe network and pumping stations is 8,328,451 yuan. The comparison of cumulative total annual cost before and after optimization is presented in Figure 7. Therefore, through optimization analysis, a pumping station could have been eliminated in the study project in a developing municipal region in Taizhou, China, saving 3,461,847 yuan. In addition, 63,391 yuan of energy cost can be saved annually.

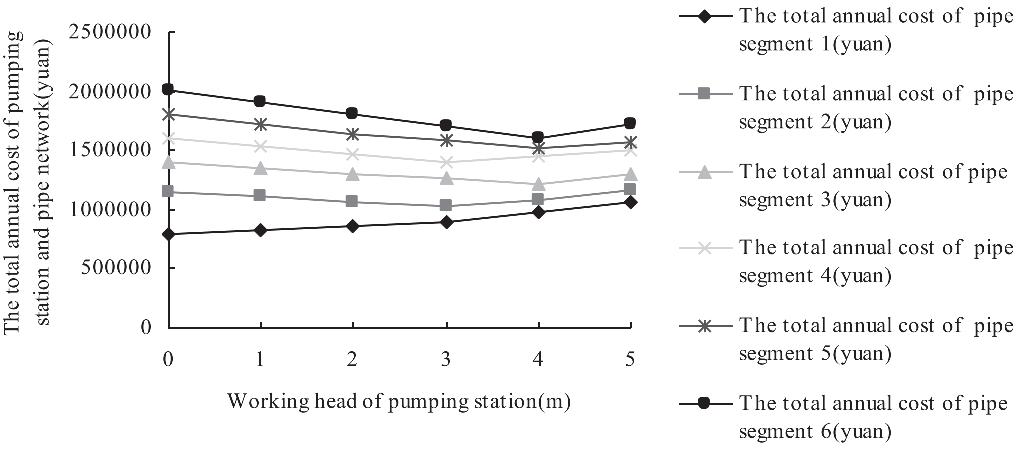

Fig. 6. Relationship between the total annual cost of a pipe section and the working head of a pumping station.

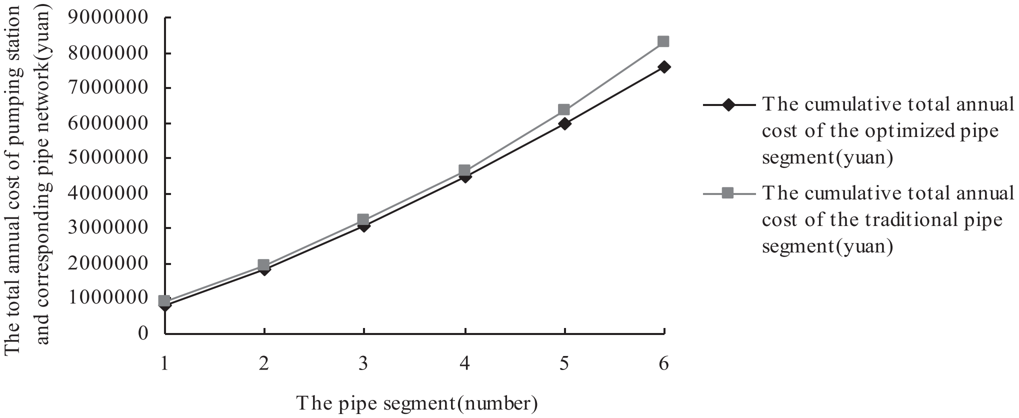

Fig. 7. Comparison of cumulative total annual cost before and after optimization.

4. Optimization results analysis and discussion

Application of the orthogonal test and dynamic programming method proposed in this paper led to several key results regarding the optimal design of a sewage pipe network and pumping stations in a developing municipal region of Taizhou, China.

(1) The orthogonal test selection for the layout and the working head of the sewage pumping stations had a noticeable effect on the optimization of the layout of the sewage pumping stations and sewage pipe network. The optimization results indicated that sewage pumping stations should not be built, when the diameter and buried depth of the pipes have little effect on the annual cost. Consequently, Pumping Station 1 in the case study could have been eliminated. The annual cost determined using the optimization method proposed in this paper could have been reduced by 10.2%, highlighting the practical and economic value of the optimization procedure.

(2) Results shown in Table 3 indicate that the sewage flow at both ends of a branch pipe is the same. However, the downstream pipe diameter is not determined solely by the upstream pipe diameter. Instead, the branch pipe diameter should be determined based on the head, sewage flow rate and pipe length of the branch pipe section. In addition, the downstream pipe diameter of a non-pressurized pipe network should be greater than or equal to upstream pipe diameter.

(3) Figure 6 shows that the influence of a sewage pumping station on the annual cost of sewage network increases as sewage flow rate increases. There is no need for a sewage pumping station when the sewage flow rate is 0.231 m3 s-1 and including the pumping station will unnecessarily increase the annual cost. The annual cost can be reduced by 10.5% by setting up sewage pumping stations, when sewage flow rate is 0.408 m3 s-1. When sewage flow rate reaches 1.155 m3 s-1, the cost can be reduced by 18.5%.

(4) Figure 6 shows that the hydraulic heads at pumping stations have a noticeable effect on the annual cost of a sewage pipe network. However, the correlation between cost saving and head is not positive because pipe diameter is influenced by sewage flow rate. When the heads at sewage pumping stations 2 and 4 reach 3 m, annual cost can be minimized. However, when the heads at sewage pumping stations 3 and 4 reach 4 m, the annual cost is also minimized. Therefore, an optimization process is necessary for the optimal design of the layout of the sewage pumping stations and the corresponding pipe network.

(5) Figure 7 shows that the influence of the optimal design proposed in this paper increases with the number of sewage pumping stations and the length of the sewage pipe network. The comparison of cost of an un-optimized system and that of an optimized system show that the annual cost of Pipe Section 1 (Table 1) can be reduced by 99,693 yuan, which is not significant. However, the combined savings on Pipe Section 2 to Pipe Section 6 is approximately 849,500 yuan, which is significant. Therefore, the optimization method proposed in this paper is more beneficial for the optimization of regional-scale sewage pipe and pumping station networks than for smaller systems.

5. Conclusions

(1) In this paper, a new method for the optimal design of the layout of the pumping stations and sewage pipe network was proposed. The technique is based on an orthogonal test and a subsystem model that uses the dynamic programming method. The sub-system model is expanded into a large-scale model that can optimize the location of pumping stations, hydraulic head and pipe diameters within the network.

(2) The optimization method presented in this paper is capable of delivering obvious economic benefits by minimizing the number of pumping stations and annual operating cost and optimizing the working head of the pumping stations and the pipe diameter of the pipe network.

(3) The optimization method proposed in this paper can be applied to different sizes of sewerage networks, but is more beneficial for the optimization of larger, regional-scale sewage pipe and pumping station networks.

(4) The optimization method presented in this paper can provide a reference for optimization research on the planning and layout of centralized sewage treatment plants connected to pumping stations and a pipeline network.

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إيجاد الحل الأمثل لتكلفة التشغيل لنقل الصرف الصحي

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الملخص

التمدن المتسارع يتسبب في اجتياح غير عادي لشبكات الصرف الصحي. لذلك، فإن استخدام طرق إيجاد الحل الأمثل لتحسين تصميم هذه الشبكات يكون له تأثير عملي. في هذا البحث، تم تطوير نظام فرعي للنمذجة غير الخطية لإيجاد الحل الأمثل لتكلفة التشغيل لنقل الصرف الصحي. تم توسيع النظام الفرعي إلى نظام مركب على نطاق واسع للنمذجة غير الخطية لإيجاد الحد الأدنى لإجمالي التكلفة السنوية لمحطة الضخ وشبكة جميع قطاعات الأنابيب. تم وصف طرق اختبار الاختيار للنظام الموسع وطرق النمذجة الديناميكية للنظام الفرعي. تم عمل مقارنات باستخدام شبكة الصرف الصحي في مدينة تايزو – الصين كمثال للتوضيح. وضحت الدراسة أنه سيكون هناك توفير واضح في التكلفة إذا تم استخدام النظام المقترح في هذا البحث لإيجاذ الحل الأمثل. كما يمكن تخفيض التكلفة السنوية لنقل الصرف الصحي في هذه الحالة بنسبة 10.6%. الطريقة المقترحة لها قيمة عملية لإيجاد الحل الأمثل لمشاريع الصرف الصحي في المدن وتعطي مرجع للأبحاث النظرية في هذا الموضوع.